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A COMPACT, LOW-COST, FORCED-CONVECTION HELIUM CAPSULE FOR IN-PILE FUEL-ELEMENT TESTS

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ABSTRACT

A high-pressure, circulating helium capsule was designed and built for in-pile testing high-performance gas-cooled reactor fuel elements. Helium cooling capability of this circulating capsule, including total nuclear power and heat flux capability, is several times greater than that possible with natural convection or radiation cooled capsules. The circulating capsule design incorporates the entire helium cooling circuit (including the helium pump, heat exchanger, and fuel elements) into a single, compact unit that is located completely within the reactor shield, and fits a standard water-cooled reactor hole. The capsule thermohydraulic and mechanical design, also results of circulator flow calibration and endurance tests, are described.

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SUMMARY

The compact, gas-cooled reactor fuel-element studies at NASA-Lewis require in-pile testing of high-performance, long-life, fuel-element designs. For such testing a facility was required that was capable of maintaining fuel-element conditions of up to 3.0 kilowatts per square inch (2.84 Btu/(in.^{2})(sec) or 0.467 kW/cm^2) surface heat flux, 30 kilowatts power, at surface temperatures below 2500° F (1650 K) for 2000 to 4000 hours with inert gas cooling. Low fabrication and operating costs were of major importance.

Conventional natural-convection capsules could not be used because of their limited cooling capacity; therefore, forced-convection cooling was required. A survey of existing forced-convection loop facilities indicated that the high equipment and operating costs of such systems was prohibitive, primarily because of numerous out-of-reactor components and safety devices.

This report describes a circulating helium capsule system, which was designed and developed to meet the above requirements. The most important feature of this circulating capsule design is the integration of the entire helium circuit, including the helium circulator, heat exchanger, and fuel element, into a compact unit that fits into a 4.5-inch (11.4-cm) diameter water-cooled reactor test hole. This arrangement avoids the complexity, expense, and handling difficulties of shielded out-of-reactor components. The design can be adapted to fit reactor core holes with diameters as small as 2 inches (5.1 cm).

Development of the capsule system included checkout and flow-calibration tests of the helium circuit at motor speeds from 1800 to 4000 rpm, and helium pressures from 140 to 2500 psia (9.66×10^5 to 1.73×10^7 N/m^2) to verify operation over a range of helium flow rates from 0.010 to 0.120 pound per second (0.0046 to 0.055 kg/sec). In addition, a 6000-hour circulator endurance test has been run to qualify the capsule for in-pile testing.

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INTRODUCTION

A program at NASA-Lewis, aimed at developing high burnup fuel elements for advanced, compact, gas-cooled reactors, required in-pile testing of fuel-element designs. For testing these fuel elements at extreme operating conditions, an inert-gas-cooled test facility was required to be capable of maintaining fuel-element conditions of up to 3.0 kilowatts per square inch (2.84 Btu/(sec)(in.^{2}) or 0.467 kW/cm^2) surface heat flux and 30-kilowatt total-fission heat generation at surface temperatures below 2500° F (1650 K) for 2000 to 4000 hours.

Tests at these fuel-element surface temperatures, but lower heat fluxes, are currently conducted in high-gas-pressure, natural-convection capsules. These tests are relatively simple and inexpensive, however, the cooling capacity in natural-convection capsules is limited to fuel-element surface heat fluxes below 1 kilowatt per square inch (0.15 kW/cm^2) at the desired surface temperatures and for practical gas pressures (below 2500 psia or 1.73×10^7 N/m^2). Therefore, these high surface heat flux tests required forced-convection gas cooling.

In addition to these test requirements, other important considerations were low facility fabrication and operating cost. Various forced-convection gas loops have been designed and are in operation (refs. 1 to 4); however, these systems usually involve a great deal of out-of-reactor equipment, such as pumps, heat exchangers, and filters with associated safety devices, and are expensive to adapt and operate.

A decision was therefore made to attempt to design and develop a forced-convection capsule that would require a minimum of out-of-reactor equipment and be relatively simple and inexpensive to fabricate and operate. The resulting circulating capsule design (fig. 1) integrates a gas circulator, heat exchanger, and fuel-element test section into a single compact unit which fits into a reactor test hole and requires a minimum of out-of-reactor support equipment.

This report describes the thermal-hydraulic, mechanical, and safety design of the circulating capsule system. Herein are presented important capsule design specifications and a general description of the capsule system operation, the various thermal-hydraulics analyses required for safety evaluation and capsule component design, a description of the detailed mechanical design of capsule components, and the results of circular flow-calibration and endurance tests.

DESIGN SPECIFICATIONS

The circulating capsule was designed to meet the following requirements:

(1) Fuel-element surface heat flux up to 3.0 kilowatts per square inch (3.0 Btu/(sec)(in.^{2}) or 0.46 kW/cm^2)

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(2) Total power up to 30 kilowatts
(3) Fuel-element surface temperature up to 2500° F (1650 K)
(4) 4000-hour in-pile test capability
(5) Inert-gas coolant at a maximum pressure of 2500 psia (1.73×10^7 N/m^2) and a maximum bulk temperature of 1000° F (810 K)
(6) Coolant-gas impurity content, less than 50 ppm
(7) Minimum radiation and contamination hazards to personnel and reactor facility
(8) Continuous monitoring for fuel-element fission product leak
(9) Low fabrication and operating cost
(10) Maximum capsule outside diameter, 4.5 inches (11.4 cm)

GENERAL DESCRIPTION OF CAPSULE SYSTEM

The circulating capsule system (fig. 1) consists of the circulating capsule and its control console. The capsule, with its most important components identified, is shown fully inserted in a water-cooled test hole during in-pile testing. A more detailed capsule assembly drawing is presented in figure 2. The capsule assembly consists of the sealed pressure vessel with the fuel-element test section at the reactor end, the helium circulator at the shield end, and the helium-to-water heat exchanger connecting these ends. Helium was chosen as the inert-gas coolant because of its low pumping power requirements; however, the capsule is not restricted to operation with helium.

The capsule operates in the following manner. High-pressure helium is pumped through the center tube of the heat exchanger to the fuel element, where it removes the fission heat and then flows back through the annular passage of the heat-exchanger section where this heat is transferred to the reactor facility water system. Helium pumping power is provided by a circulator consisting of a vane pump driven by a variable-speed electric motor. A wide range of helium flow rates for fuel-element temperature control can be obtained by proper combinations of helium pressure and motor speed. The capsule operation is monitored and controlled from a remotely located console which contains the variable frequency motor power supply, helium pressure and bleed flow controls, pressure and temperature recorders, and alarms.

The circulator end of the capsule is located in the reactor shield sufficiently far from the reactor core to assure low radiation levels and minimize radiation damage to the circulator components. To detect specimen fission product leak, a small helium bleed flow is maintained to the fission product monitor, which requires makeup from a high-pressure helium supply.

Operating personnel safety may be provided by shield casks or water shielding, as shown in figure 1. Provisions have been made to permit safe charging and withdrawal of the capsule from the reactor core with the reactor at full power. The sealed capsule design together with the shield casks permits testing until fuel-element fission-product leakage occurs, in which case the capsule is immediately withdrawn from the reactor core.

Damage to the capsule pressure shell in event of fuel-element meltdown, which results from accidental loss of helium flow, was regarded as the major safety problem. This problem was solved by providing a tungsten catcher tray at the fuel-element end to catch materials that may melt in event of helium flow loss and to safely dissipate the fission heat without damage to the capsule pressure shell. The capsule pressure shell diameter at the circulator end is 4.3 inches (10.9 cm), which is the smallest diameter into which the present motor and pump can be packaged. The shell diameter at the heat exchanger is 1.9 inches (4.8 cm). The fuel-element end shell diameter, depending on the size of the fuel-element test section and catcher tray, can be as small as 2.0 inches (5.1 cm).

The capsule is presently designed for horizontal operation, but with a redesigned means of containing a fuel-element meltdown, it could be operated vertically.

HEAT-TRANSFER AND FLUID-MECHANICS ANALYSES

These heat-transfer and fluid-mechanics analyses were required (1) to show safety of the capsule design at maximum power with regard to fuel-element meltdown and helium cooling capacity and (2) to determine flow rates and fuel-element flow passage geometry for specified test conditions of surface temperatures and heat fluxes.

Capsule Heat Removal Capability

The 30-kilowatt capsule power requirement affected the capsule design in two ways. First, preliminary estimates indicated that the helium temperature rise along the fuel element would be in the range of 200° to 600° F (111 to 334 K), with a nominal rise of 400° F (222 K). This corresponds to a nominal circulator capacity of 0.057 pound per second (0.026 kg/sec) for the 30-kilowatt system. For conservatism, twice this flow rate or 0.114 pound per second (0.052 kg/sec) was chosen as the value that determined the choice of circulator design. Second, in the event of helium flow loss, another means of redistributing the maximum heat generated had to be provided. Because, in the worst case, the fuel elements would melt on loss of helium flow, a tungsten catcher tray was designed that would contain the molten fuel elements and their holder without damage to the capsule walls and that would also have sufficient surface area to radiate the 30 kilowatts to the capsule walls.

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Heat Exchanger

The heat picked up by helium from the fuel element is transferred in a specially designed concentric-tube heat exchanger section to the water surrounding the capsule. The concentric tubes provide flow passages for the supply and return helium. Sufficient length-to-hydraulic-diameter ratio is provided in the hot helium side annular passage to cool the helium from the 1000° F (810 K) maximum at the element end to below 200° F (367 K) at the circulator end. This ensures a cool environment for circulator. The cold helium side is sized to minimize pressure drop.

For mechanical simplicity the hot and cool helium streams are not insulated from each other and some regenerative heating of the supply side helium occurs. The helium temperature at the ends of the concentric tube heat exchanger were calculated from a heat-transfer analysis that accounted for both water cooling on the return helium side and regeneration on the supply helium side. These helium temperatures for the selected concentric tube dimensions are shown in figure 3 as functions of helium flow rate for the 30-kilowatt maximum power. These temperatures are primarily functions of the fixed heat-exchanger dimensions, and their relative values are essentially independent of total power. The regenerative heating of the supply helium stream did not restrict performance of the circulating capsule in any way, and, because it was actually desirable to operate with the preheated helium for fuel-element tests, no steps were taken to eliminate regeneration. The degree of regenerative heating in any future design could be easily controlled, retaining the present tube dimensions, by inserting the proper length of a third, light gage, concentric tube to provide an insulating static-gas layer either (1) between the hot and cold helium stream, resulting in less regeneration, or (2) between the hot helium stream and the water-cooled capsule shell, resulting in increased regenerative heating of the supply gas stream.

Fuel-Element Flow-Passage Size for Specified Heat Flux and Surface Temperature

The fuel-element test section described in this report is designed for fuel-element pins. However, with simple fuel-element holder modifications, the capsule can be readily adapted to testing other fuel-element configurations such as flat plates or honeycomb matrices.

This section describes the procedure used to calculate the required length-to-hydraulic-diameter ratio L/d of the fuel-pin annular helium flow passage as a function of helium flow rate, for specified values of fuel-pin surface temperature, fuel-pin dimensions, and surface heat flux. Data such as these will be used later to determine the flow

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requirements and other operating conditions for a specified test.

A computer code was written to calculate the surface temperature profile along the fuel pin. This code includes a standard forced-convection heat-transfer coefficient correlation. Because the temperature profile may be strongly affected by heat conduction along the pin to the unfueled end supports, this effect was accounted for in the calculations. The fuel-pin temperature reaches a peak value downstream of the pin midpoint. All references to fuel-pin surface temperature in this report are this peak temperature.

This heat-transfer code was used, together with helium inlet and exit temperatures from the heat-exchanger analysis (fig. 3) to determine the required annular flow passage L/d as a function of helium flow rate for a specified fuel-pin surface temperature. The results of such a calculation for a 30-kilowatt fuel pin with 2.0 kilowatts per square inch (0.31 kW/cm^2) surface heat flux are shown in figure 4.

As will be explained in the next section, the operating helium flow rate is generally chosen at the nominal helium temperature rise along the fuel pins of 400° F (222 K). In general then, for the same pin temperature and heat-flux conditions, the required annular flow passage area for various tests is nearly proportional to the test power or fuel-pin length.

Circulator Flow Calibration and Helium Flow-Rate Capacity

Because the vane-pump volumetric efficiency varies with the helium circuit flow resistance, a series of helium flow-calibration tests was run on a complete capsule mockup to determine helium flow rates as a function of pressures and motor speeds for various fuel-pin flow-passage dimensions. These dimensions, which are the most important factors that govern the helium circuit pressure drop, were determined by the calculation procedure described in the previous section. For the flow calibration tests, the range of fuel-pin flow-passage pressure drops was simulated by four different equivalent-diameter orifice plates with diameters of 0.193, 0.275, 0.340, and 0.396 inch (0.490, 0.698, 0.863, and 1.00 cm). This range of orifice diameters corresponds to fuel-element flow passage dimensions for the range of power from 6.0 to 30 kilowatts and heat flux from 1.0 to 3.0 kilowatts per square inch (0.155 to 0.465 kW/cm^2). Circulator flow calibration and endurance tests are discussed in greater detail in a later section.

The complete set of flow calibration test data is shown in figure 5. These flow-calibration curves may be used for helium flow-rate estimates in a specific test with known flow-passage dimensions by calculating the equivalent orifice diameter and interpolating on the flow calibration curves in figure 5.

The orifice diameter of 0.396 inch (1.00 cm) in figure 5(d) corresponds to a typical 30-kilowatt fuel-pin flow passage. These test data show that a flow rate of 0.057 pound

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per second (0.026 kg/sec) (corresponding to 400° F (222 K) nominal helium temperature at a maximum 30 kW power) can be obtained at 1940 rpm motor speed and 2000 psia (1.38×10^{7} N/m^{2}) helium pressure. The maximum tested circulator capacity was 0.120 pound per second (0.055 kg/sec), obtained at 3500 rpm and 2500 psia (1.73×10^{7} N/m^{2}). These results together with the endurance test results indicate that, for the present circulator design and fuel-element power up to 30 kilowatts, the operating helium flow rate corresponding to a 400° F (222 K) helium temperature rise is a reliable choice for test durations of up to 4000 hours.

In general the, the operating helium flow rate for a specific test can be confidently selected for a helium temperature rise of 400° F (222 K) along the fuel element. It is important to note here that this selection criterion results in a maximum helium bulk temperature, as may be determined from figure 3, of about 600° F (588 K), which is well within the capsule design limit of 1000° F (810 K).

Selection of Helium Operating Conditions and Flow-Passage Size for Representative Experiment

In order to illustrate the procedure of using the results of thermohydraulics calculations and circulator flow tests for selecting capsule operating conditions, a representative experiment is treated herein.

For this representative experiment, the fuel-pin conditions, specified by test objectives, are

(1) Two identical pins of specified length and diameter run in parallel
(2) Total power, 15.7 kilowatts
(3) Surface heat flux, 2.0 kilowatts per square inch (0.31 kW/cm^{2})
(4) Peak pin surface temperature, 2500° F (1650 K)
(5) Test duration, 4000 hours

For these specified fuel-pin conditions, the capsule operating conditions will now be determined. These capsule operating conditions include helium temperatures and flow rate (combination of helium pressure and motor speed), and fuel-pin flow passage size.

The helium temperatures, which were calculated as a function of helium flow rate for the specified 15.7-kilowatt power using the previously described heat-exchanger analysis, are shown in figure 6(a). The required fuel-pin flow-passage L/d for 2500° F (1650 K) surface temperature, which was calculated by the procedure described in a previous section on fuel-element flow-passage size, is also shown as a function of helium flow rate in figure 6(a).

Using the criteria for operating helium flow-rate selection established in the previous section, the operating helium flow rate is calculated as 0.030 pound per second (0.0137 kg/sec), which corresponds to the hot helium temperature in figure 6(a) of 610° F (595 K). The flow passage length-to-hydraulic-diameter ratio, which sizes the annular flow passage area for the fuel pin holder design, is then determined as $L/d = 46.0$ (fig. 6(a)).

The operating helium pressure and motor speed remain to be determined. The equivalent orifice diameter of 0.325 inch (0.825 cm) is first calculated for the annular flow passage having the specified pin dimensions and the previously determined value of $L/d = 46.0$. This value of equivalent orifice diameter is used with the flow calibration test data of figure 5 to arrive at an interpolated graph of flow rate against pressure and motor speed (fig. 6(b)). For maximum circulator reliability over the 4000-hour test duration, a low operating motor speed of 2000 rpm is chosen. The operating helium pressure of 1000 psia (6.90×10^6 N/m^2) is then found using figure 6 with the 2000-rpm motor speed and 0.030 pound per second (0.0136 kg/sec) flow rate.

The complete set of expected capsule operating conditions for this representative experiment has now been determined and is summarized as follows:

Specified Conditions:	
Number, length, and diameter of fuel pins	
Total heat generation, kW	1.57
Surface heat flux, kW/in.^{2}; kW/cm^2	2.0; 0.35
Peak pin surface temperature, °F; K	2500; 1650
Calculated Conditions:	
Helium inlet temperature, °F; K	210; 373
Helium outlet temperature, °F; K	610; 595
Helium temperature at circulator, °F; K	110; 317
Helium flow rate, lb/sec; kg/sec	0.030; 0.0136
Flow passage, L/d	46.0
Motor speed, rpm	2000
Helium pressure, psia; N/m^2	1000; 6.90×10^6

CAPSULE AND SYSTEM MECHANICAL DESIGN

Compressor

The following criteria were used in selecting the compressor:

(1) Maximum outside diameter including pressure shell of 4.3 inches (10.9 cm)

(2) Flow rate of 0.114 pound per second (0.052 kg/sec) of helium with an estimated volumetric efficiency of 70 percent and pressure rise of approximately 10 psia (6.9×10^4 N/m^2) at static pressure levels on the order of 2000 psia (1.38×10^7 N/m^2)

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(3) Radiation restrictions on materials - especially on lubricants

(4) Simplicity and low cost

These requirements, in particular, steady, low-volume flow and high volumetric efficiency, eliminated centrifugal, multistage axial flow and piston compressors. An axially long-positive displacement, vane compressor was adapted by reversing the direction of rotation of a pneumatic hand grinder motor. This type of compressor is relatively insensitive to changes in flow resistance. The only modification that was necessary was a change from linen reinforced phenolic to graphite vanes. Graphite was selected for its high resistance to radiation damage and its self-lubricating characteristics. Sample vanes of linen reinforced phenolic and polytetrafluoroethylene were also fabricated and tested but were found unsatisfactory due to radiation induced embrittlement. The compressor has a displacement of approximately 3.5 cubic inch per revolution (57.3 cc/revolution). A specially designed housing serves as a cartridge into which the compressor, motor, and tachometer are assembled (see figs. 2 and 7). This housing provides all compressor porting, bearing supports and thermocouple passages. This is the only complex part in the entire capsule, but it permits testing of the completed circulator assembly before the circulator is seal welded into the capsule.

Another type of compressor that would have a high probability of success would be a Roots or lobed-rotor type. The added advantage of this compressor would be the elimination of gas-stream contamination which presently results from graphite dust because of the slight vane wear. An unsuccessful search was made to locate a source of miniature lobed-rotor compressors. It was determined that a micron pore size sintered metal filter could be procured and installed to eliminate the graphite dust at lower cost than the development of a custom-designed miniature lobed compressor.

Motor and Power Supply

The motor selection criteria were as follows:

(1) 1 to 2 shaft horsepower (750 to 1500 W) required based on minimum overall circulator efficiency of 2 percent

(2) Speed range and variability (1500 to 5000 rpm) necessary to satisfy compressor flow-rate requirements

(3) Maximum outside diameter including pressure shell of 4.3 inches (10.9 cm)

(4) Use of radiation resistant materials

(5) Use of existing motor fabrication techniques

A source of small diameter, axially long motors was located (E.M.D. Company of Wickliffe, Ohio) and a three-phase variable-frequency squirrel-cage radiation-hardened motor rated for 2 horsepower (1500 W) at 10 000 rpm was designed and procured. Provision was incorporated for an integral rotating magnet tachometer and for driving the com-

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pressor directly from a motor shaft extension. Because of the long shaft and unsymmetrical loading, a three-bearing design was used (see figs. 2 and 7). A low-vapor-pressure radiation-resistent ball bearing lubricant was used.

A solid-state power supply was also procured from E.M.D. Company. This power supply has an output frequency continuously variable from 25 to 90 cps (25 to 90 Hz). The power supply converts the three-phase, 440-volt, 60-hertz power available at the reactor to suitable three-phase voltage for the motor (approximately 1.4 V/Hz). A nearly constant torque results, which is ideal for the compressor load.

Heat Exchanger

The heat-exchanger design was dictated by the following considerations:

(1) The length required to connect the fuel elements located in the core with the circulator located in the shield region

(2) Flow passage and heat-transfer area required to reduce the helium temperature from 1000° F (810 K) at the fuel-element outlet to less than 200° F (366 K) at the circulator over the required flow range with minimum pressure drop

(3) Mechanical strength and rigidity

(4) ASME Pressure Vessel Code shell design

(5) Simplicity and low cost

The result was an annular concentric tube exchanger using standard stainless-steel pipe sizes. The outer tube is a 1.90-inch (4.8-cm) schedule 80 pipe and the inner tube is a 0.75-inch (1.9-cm) schedule 10 pipe. Sufficient length-to-diameter ratio was used to ensure that the returning gas could be cooled to prevent the compressor temperature from exceeding 200° F (366 K). With this design, a slight amount of regenerative heating occurs as is described in the Heat-Transfer and Fluid Mechanics Analyses section.

A 2-percent borated stainless-steel shield plug was installed in an enlarged section of the return tube near the compressor (see fig. 2). This plug is larger in diameter than the outer heat-exchanger tube bore and prevents neutron and gamma radiation from streaming down the tube, thus protecting the motor and compressor. The shield plug is supported and cooled by axial fins that conduct any radiation induced heat out to the cooling water.

Fuel Element and Holder

Design criteria for the fuel-element holder were

(1) Number, length, and diameter of the fuel pins

(2) The size of the radial gap between the pin and the gas flow tube

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(3) Expected temperatures

(4) Thermal expansions

(5) Neutron attenuation

(6) The provision for thermocouples

These criteria led to the design of a molybdenum fuel-element holder as shown in figures 8 and 9. Provision is made for the installation of up to seven fuel-element thermocouples. The thermocouple installation was devised to provide the best possible indication of the true fuel-pin temperature. A heat-transfer computer code, referred to in the Heat Transfer and Fluids Mechanics Analyses section, was used to correlate the temperature at the thermocouple with the peak-pin surface temperature.

Provision is also made for one thermocouple each in the supply and exit gas streams. The fuel-element holder, with all thermocouples in place is designed to be screwed into the end of the center gas supply pipe. It is lockwired in place before welding on the end cap.

Catcher Tray

Experiment safety considerations led to the design of a half cylindrical tungsten catcher tray (fig. 9) into which the fuel pins and holder would fall should the gas flow cease and meltdown occur.

The design criteria for the catcher tray were

(1) Tray volume greater than the fuel-pin material volume

(2) Sufficient tray surface area to redistribute 30 kilowatts without damage to capsule pressure shell

The half, rather than full, cylindrical shape resulted from nuclear attenuation considerations; therefore, precautions must be taken to ensure that the catcher tray is in its proper position during insertion into the reactor. The catcher tray is supported on lugs, thus limiting heat conduction to the pressure shell. Its length is designed such that it will contain the entire molten volume of fuel elements and holder and could radiate the 30 kilowatts fission heat at 4500° F (2760 K), a temperature well within the thermal and mechanical strength limitation of the tungsten.

Additional safety factors during any accidental meltdown would be provided by the free thermal convection within the helium and by the fact that the fuel will vaporize and condense on the cool pressure shell walls, thus distributing the heat source over a larger area.

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Containment Vessel

Design criteria for the containment vessel were

(1) Maximum outside diameter, 4.5 inches (11.4 cm)

(2) Maximum helium pressure, 2500 psia (1.73×10^7 N/m^2)

(3) Maximum containment vessel temperature, 1000° F (810 K)

The result was a stainless-steel ASME Code designed pressure vessel, capable of withstanding 2500 psia (1.73×10^7 N/m^2) internal pressure at temperatures up to a maximum of 1000° F (810 K).

Static-sealed penetrations for electrical connections, bleed gas, bleed gas make-up, and 10 thermocouples exit the vessel at the shield end. Here a redundant bulkhead is provided, which is also designed for 2500 psia (1.73×10^7 N/m^2).

The entire pressure vessel, with the exception of the larger diameter housing at the motor end, is fabricated of standard schedule 80 stainless-steel pipe and fittings. The internal parts are standard schedule 10 stainless-steel pipe and fittings.

The entire vessel was designed to facilitate the essential procedures of seal welding, radiography, pneumatic pressure testing, and helium mass spectrometer leak detection.

A long tube is welded to a cone at the motor end of the vessel. This tube serves as the charging rod and also as a conduit for electrical leads, instrumentation leads, and the helium bleed and supply tubes.

Instrumentation and Control

Figure 10(a) shows the instrumentation and flow control diagram. All experimental instrumentation and control apparatus, including the solid-state, variable-frequency-motor power supply, is contained within a single three-bay console as shown in figure 10(b). Instrumentation for the experiment can be divided into three groups: (1) control, (2) data gathering, and (3) experiment safety.

Control instrumentation. - The following items are to be manually controlled

(1) Capsule helium pressure

(2) Motor speed

(3) Helium bleed flow rate

The circulating helium flow rate and fuel-pin surface temperature are controlled by means of helium pressure adjustment and motor speed adjustment. Helium is supplied from a bank of 3500-psia (2.4×10^7-N/m^2) cylinders that feed a high-pressure helium manifold. The manifold supplies gas to a pressure regulator by means of which the desired capsule internal pressure is set. An isolation valve is provided to shut off the supply line in the event of a rupture. The helium supply system is provided with local pres-

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sure gages and an overpressure relief valve. The capsule internal pressure is continuously recorded on a strip chart recorder. A small helium bleed (~20 atmospheric cc/min) from the experiment is maintained through a radiation monitor to check for fission product leakage. Bleed flow is regulated by means of a micrometer needle valve and is observed on a rotameter. The rotameter is protected by a relief valve. All system relief valves dump into the facility hot (contaminated) exhaust system. Motor speed control is accomplished via a multiturn potentiometer which is connected to the variable-frequency power supply. Local meters showing the voltage, frequency, and current were provided. The motor speed signal from the tachometer is continuously recorded.

Data gathering instrumentation. - Data are gathered from the following sources:

(1) A maximum of seven fuel-element temperature thermocouples connected to a multipoint recorder.

(2) Three gas-temperature thermocouples connected a second multipoint recorder. These are located at the compressor inlet, at the inlet to the fuel element, and at the outlet from the fuel element.

(3) A motor speed recorder

(4) A capsule pressure recorder

These last two items are connected to a third recorder.

Experiment safety instrumentation. - In addition to the indicators and gages as outlined under Control and Data gathering instrumentation, alarms are provided in the event of

(1) Motor overcurrent

(2) Fuel-element overtemperature

(3) Gas overtemperature

(4) Fission product leakage

(5) High or low capsule gas pressure

(6) High or low bleed gas flow

Display is made of all alarm condition causes on a resettable alarm panel.

Production Model Tests

Each test capsule undergoes the following test sequence after completion of fabrication:

(1) Radiography of all pressure vessel welds

(2) Pneumatic pressure test to 3140 psia (2.16×10^{7} N/m^{2})

(3) Helium mass spectrometer leak test at 1500 psia (1.04×10^{7} N/m^{2}) of all welds and seals, to less than 10^{-5} atmospheric cubic centimeter per second total leak rate

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(4) Ground (hypot) and resistance tests on all motor and tachometer leads

(5) Ground and resistance tests of all thermocouples

(6) Bake-out and simultaneous evacuation of the assembly for 10 hours at 200° F (370 K) and below 0.050 torr (6.6 N/m^2) absolute pressure

(7) Operation of the motor at fixed speed from 3-phase 60-hertz supply with stethoscopy for unusual noise

Following these tests the assembly is backfilled with pure helium to approximately 40 psia (2.7×10^5 N/m^2), crated and shipped to the reactor with the long lead tube disconnected.

CALIBRATION AND CHECK-OUT TESTS

Flow Calibration Tests

These tests were run with fuel-element pressure drop simulated by various size calibrated orifices (0.193-, 0.275-, 0.340-, and 0.396-inch (0.490-, 0.698-, 0.863, and 1.00-cm) orifice diameters) to obtain data which showed the variation of helium flow rate with motor speed and pressure for a wide range of fuel-element configurations. The tests were conducted with motor speed ranging from 1800 to 4000 rpm and helium pressures from 140 to 2500 psia (9.66×10^5 to 1.73×10^7 N/m^2). These data are presented in figure 5. Testing was limited to below 4000 rpm motor speed, which at that time was considered a safe limit for the motor-pump combination. Operation above 4000 rpm may be possible, but would have to be demonstrated with endurance tests at the high motor speeds.

Vane Wear Test

This test was run to determine the rate of graphite vane wear over long duration, and it also served as a preliminary endurance test. The circulator ran continuously at 900 psia (5.4×10^6 N/m^2) helium gage pressure and 2000 rpm motor speed, with several shutdowns for disassembly and vane inspection. This test was terminated after 1390 hours of operation because of a motor short, which was traced back to damage during an earlier reassembly. Comparison of vane weights taken before and after this test showed a total graphite weight loss of 0.253 gram (less than 1 percent of the total vane weight), with the wear on all vanes being nearly equal. Most of the graphite loss was due to chamfering of the vane trailing edge at an angle of 20°. All subsequent vanes have had the sharp corner prechamfered at this angle, and should experience less vane wear. From

[redacted]

the results of this vane wear test it was concluded that graphite vane wear will not affect circulator operation for as long as 4000 hours. In addition, previous materials compatibility experience indicates that this amount of graphite dust distributed throughout the capsule should not affect the results of planned fuel-element tests.

Endurance Test

One production capsule was endurance tested. This capsule system endurance test was run for over 6000 hours without any sign of motor or compressor failure. The capability for specified 4000-hour in-pile test duration was demonstrated by means of this test.

Impurity Bake-Out

A number of tests were conducted in which the capsule was evacuated, and the residual vapor pressure from bearing grease and motor insulation was measured. It was found that this vapor pressure could be reduced to below 0.050 torr (6.6 N/m^2) by baking out the circulator assembly under vacuum for 10 hours at 200° F (370 K) before assembling into the capsule.

INSERTION AND OPERATING PROCEDURE

Before insertion of the experiment into the reactor core, the following steps are taken:

(1) Repeat electrical ground and resistance checks of all leads and thermocouples and compare with data taken immediately after fabrication.

(2) Make all electrical and instrumentation connections between capsule and control console.

(3) Run motor over speed range. Check ammeter readings.

(4) Alternately evacuate capsule and purge with pure helium until desired purity level (less than 50 ppm) is achieved.

(5) Set all alarm set points. These are test dependent and are given for each capsule in a serially numbered test specification.

Insertion into the reactor core is accomplished while the reactor is operating at steady-state conditions. The following steps are performed to complete the insertion procedure.

(1) Turn on all electrical power.

(2) Test alarms and alarm panel.

(3) Set capsule helium pressure at the specified operating value.

(4) Start bleed helium flow.

(5) Start motor and set motor speed at 120 percent of the specified operating value. Note that this motor speed, coupled with a helium pressure rise of about 25 percent due to helium temperature increase, results in a helium flow rate on insertion which is about 150 percent of the specified operating flow rate.

(6) Slowly push capsule into reactor core while monitoring capsule pressure and all temperatures.

(7) Lock experiment in place when fully inserted.

(8) Adjust capsule pressure to running value.

(9) Adjust motor speed to give desired fuel-element temperatures.

(10) Check all operating parameters.

The capsule is now in normal operation. The only requirement for operational maintenance is periodic replacement of chart paper and helium supply bottles.

CONCLUDING REMARKS

The circulating capsule system was designed, fabricated, and tested. The results of circulator flow calibration and life-endurance tests, together with heat-transfer and fluid-mechanics analyses indicate that the circulating capsule system will conservatively operate in-pile at a power of 30 kilowatts for up to 4000 hours.

The capsule can be adapted to any facility where a 4.5 inch (11.4 cm) or greater diameter, water-cooled reactor hole is available. However, the hole diameter in the reactor core may be as small as 2.0 inches (5.1 cm). The fuel-element holder and helium flow passages are designed for fuel-element pins; however, modifications of the holder to permit testing of other fuel-element configurations, should not affect the capsule performance capabilities. Existing or easily available parts were used throughout in the system design, in order to keep development and fabrication costs to a minimum. Additional savings may be realized if a large number of capsules are to be tested by salvaging the circulator assembly from irradiated capsules for re-use in new capsules. The results of postirradiation examination will determine whether salvaging the circulator assembly is worthwhile.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 1, 1968,
126-15-01-03-22.

[redacted]

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2. Simon, R. H.: Design, Construction, and Initial Operation of General Atomic In-Pile Loop. Rep. GA-5938, General Atomic Div., General Dynamics Corp., Feb. 16, 1965.

3. Zasler, J.; Gnadt, P. A.; Huntley, W. R.; Kress, T. S.; and Roller, H. C.: GCR-ORR Loop 2 Design. Rep. ORNL-TM-1048, Oak Ridge National Lab., June 1965.

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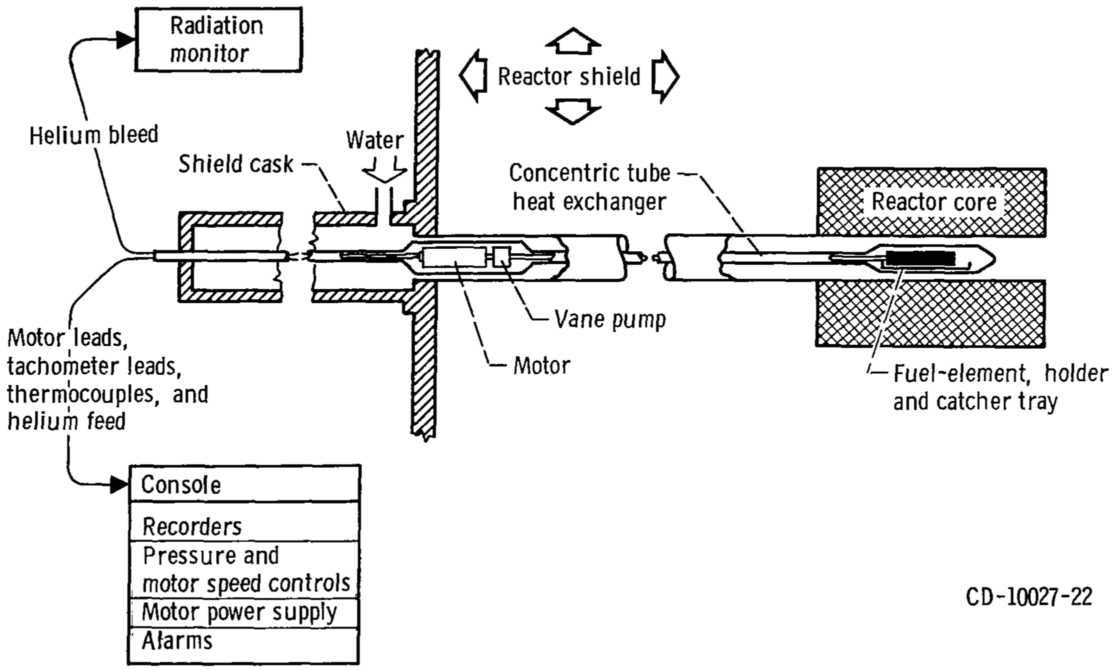

Figure 1. - Schematic of circulating capsule system during irradiation.

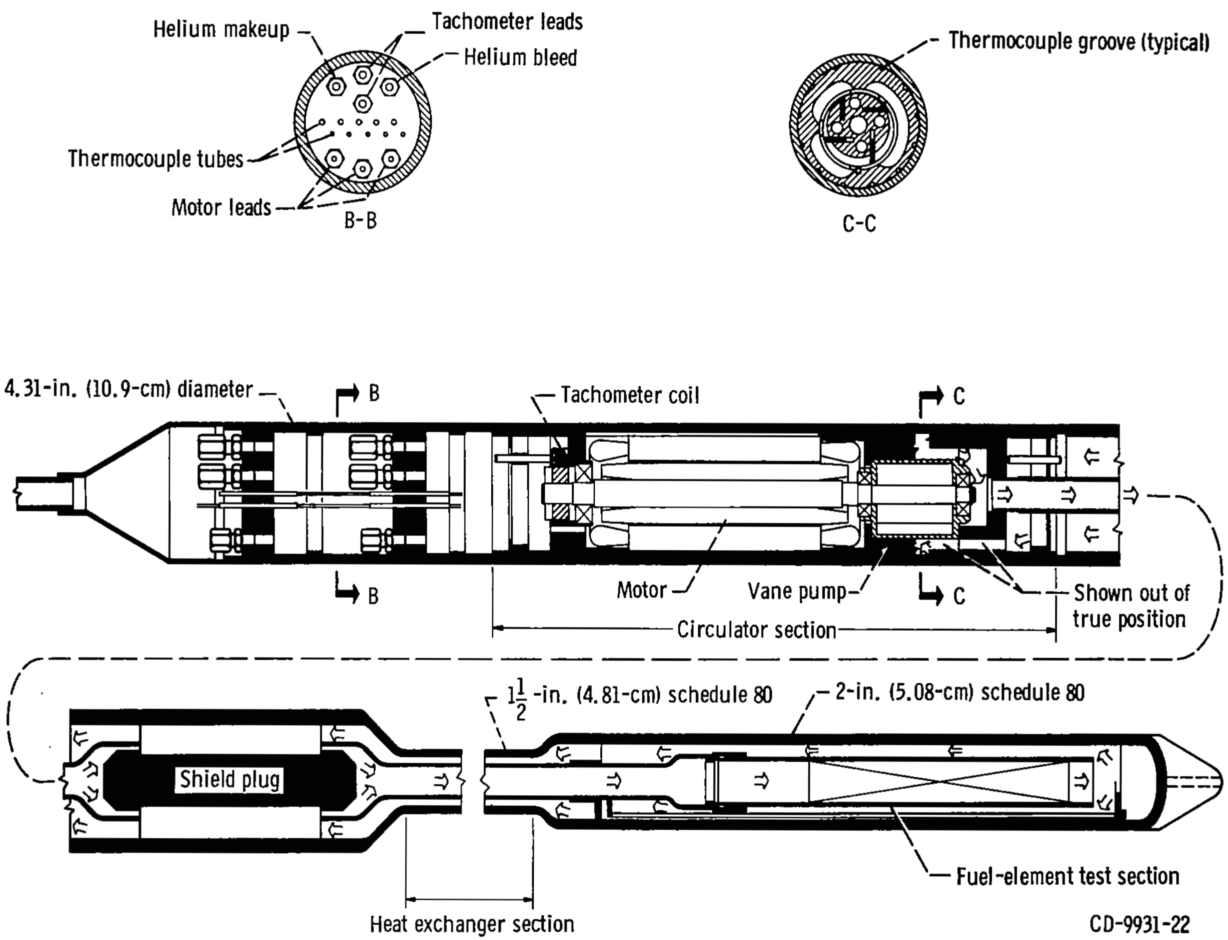

Figure 2. - Circulating capsule assembly.

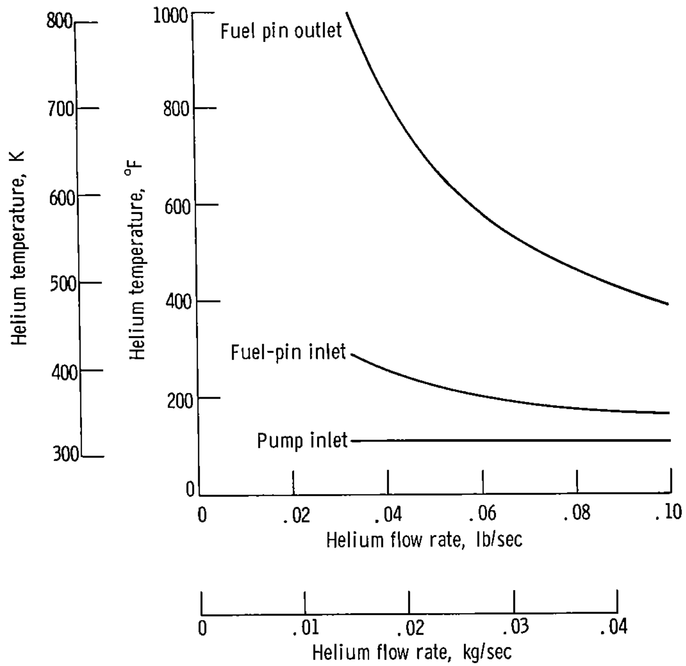

Figure 3. - Variation of helium temperature at various heat exchanger stations, with helium flow rate for 30-kilowatt test.

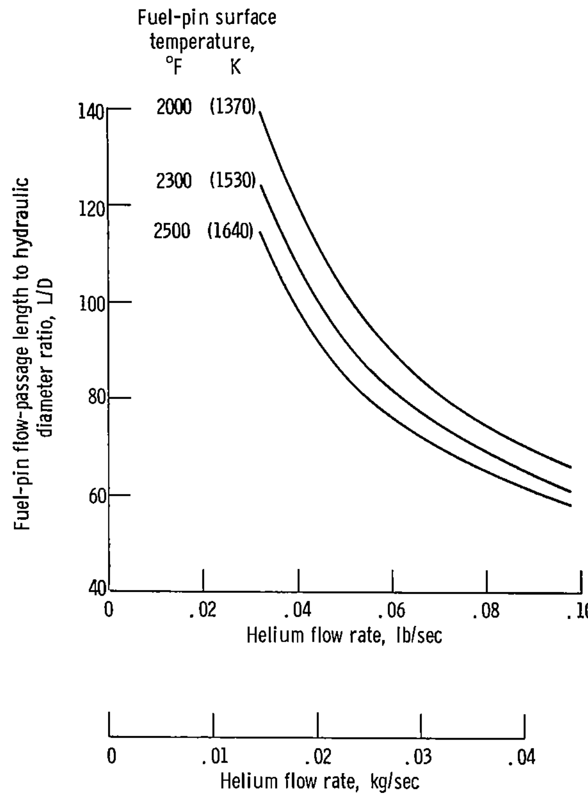

Figure 4. - Required length to hydraulic diameter ratio for various fuel-pin surface temperatures as function of helium flow rate for 30-kilowatt test. Fixed pin geometry.

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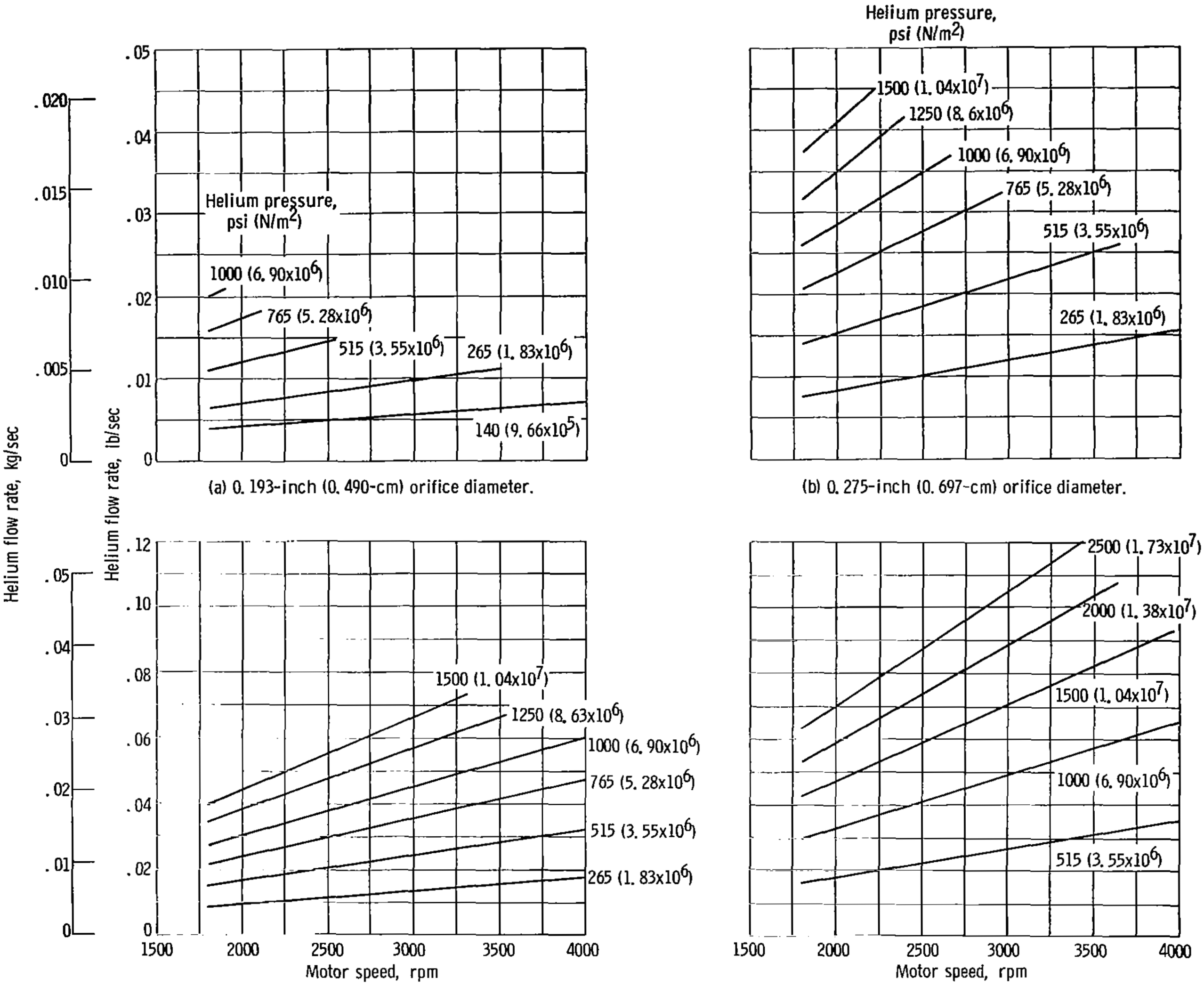

(a) 0.193-inch (0.490-cm) orifice diameter.

(b) 0.275-inch (0.697-cm) orifice diameter.

(c) 0.340-inch (0.862-cm) orifice diameter.

(d) 0.396-inch (1.00-cm) orifice diameter.

Figure 5. - Variation of helium flow rate with motor speed and helium pressure using various diameter orifices in place of test section (data from circulator calibration tests).

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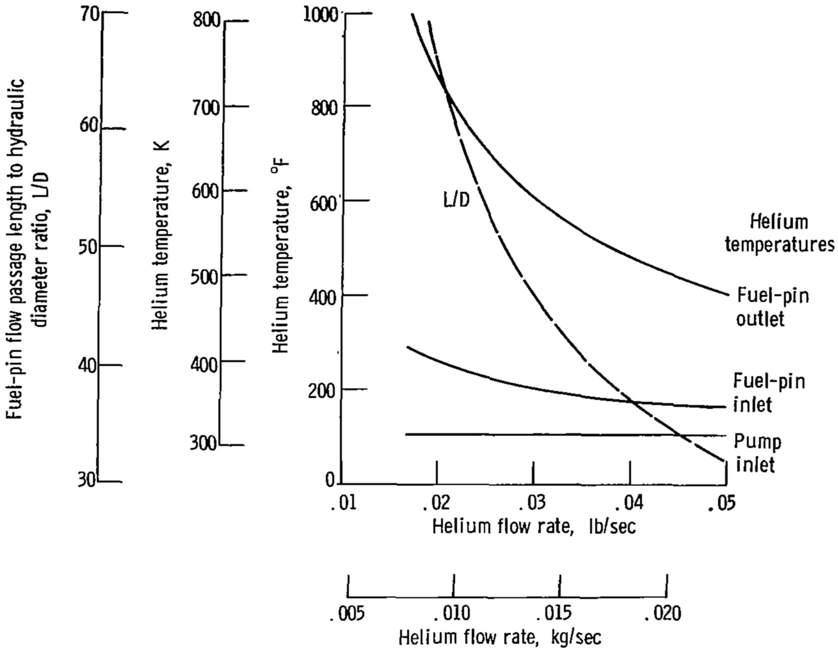
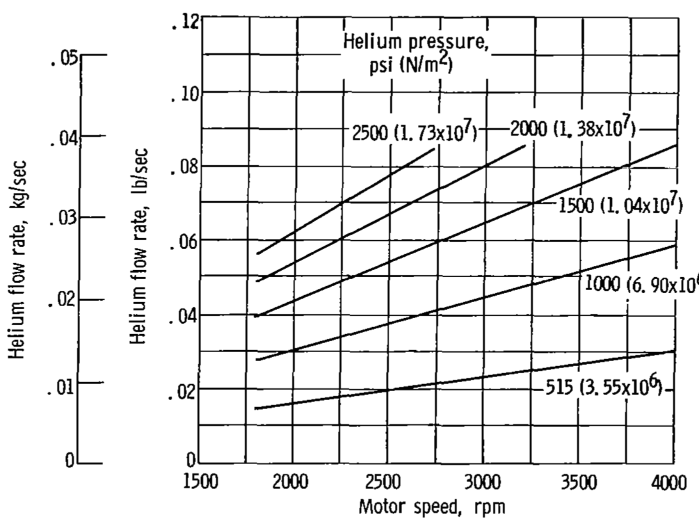


(a) Helium temperatures at various stations and flow passage length to hydraulic diameter ratio as function of helium flow rate.



(b) Variation of helium flow rate with motor speed for various pressures and 0.325-inch (0.825-cm) orifice diameter.

Figure 6. - Calculated conditions for representative 15.7-kilowatt experiment. Pin surface heat flux, 2 kilowatts per square inch; pin surface temperature, 2500° F (1644 K).

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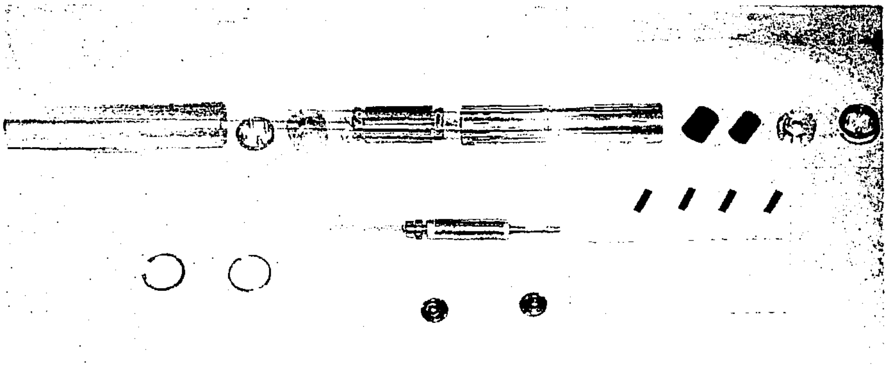

Figure 7. - Layout showing all circulator parts.

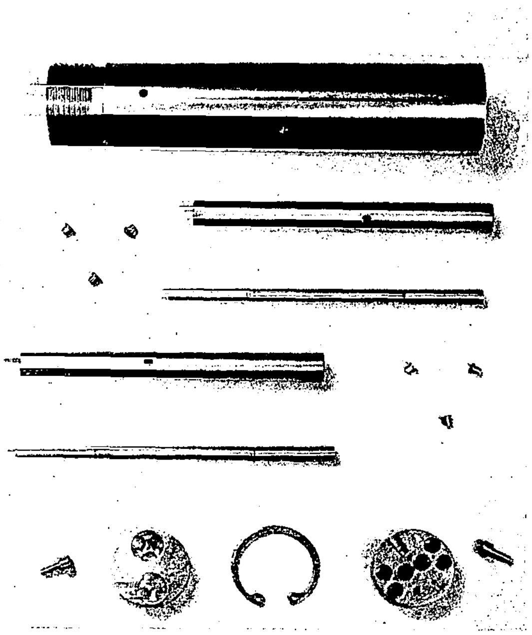

Figure 8. - Disassembled fuel pin test section.

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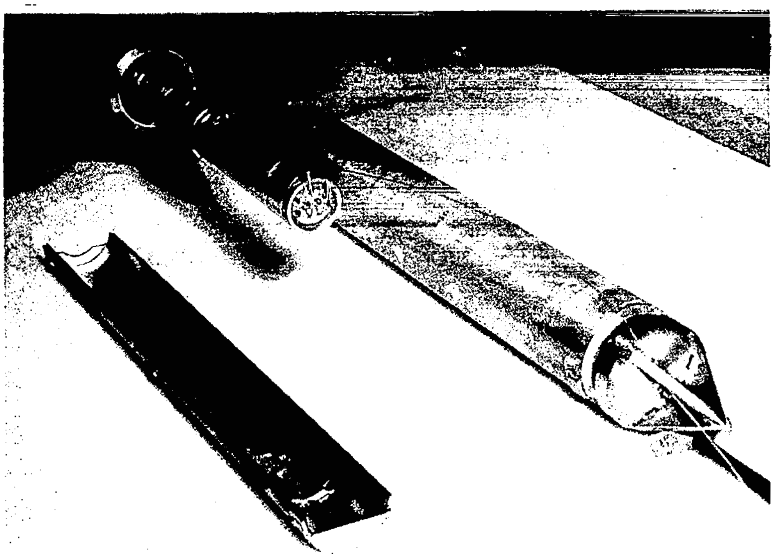

Figure 9. - Test section and catcher tray prior to final assembly.

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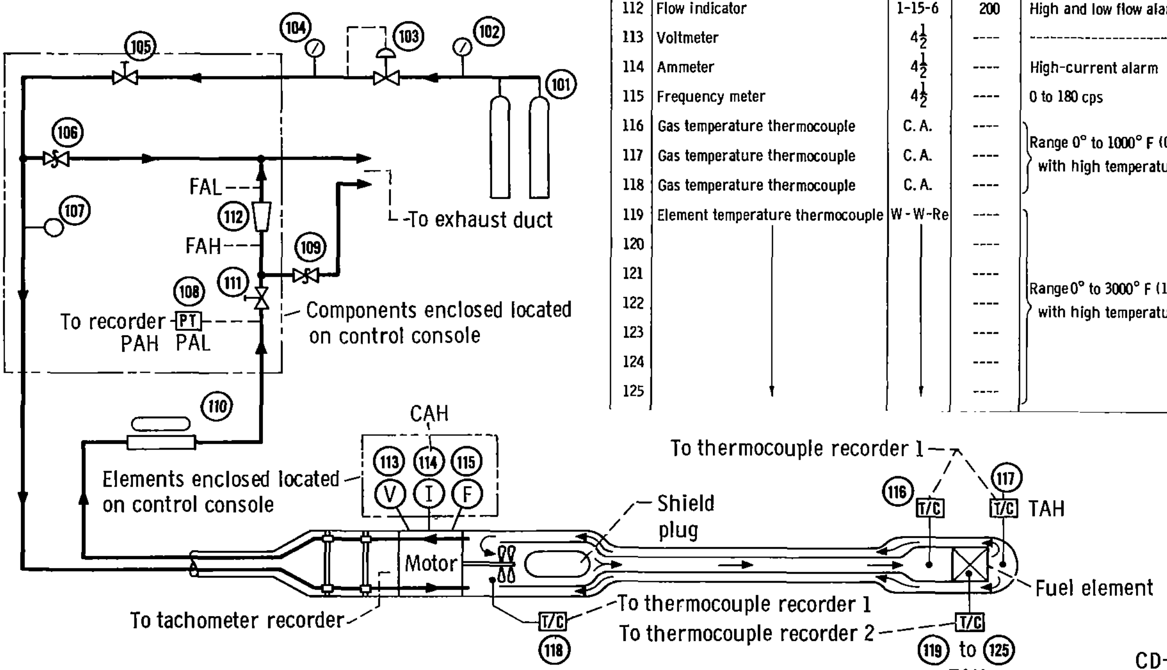
CAH High current alarm
FAH High flow alarm
FAL Low flow alarm
PAH High pressure alarm
PAL Low pressure alarm
TAH High temperature alarm

F Frequency
I Current
PT Pressure transducer
T/C Thermocouple
V Voltage

Item	Item	Type and size	Working pressure, psia	Remarks
101	Helium manifold	------	3000	At reactor
102	Helium manifold pressure gage	------	4000	On regulator 103
103	Helium supply regulator	$\frac{1}{4}$ NPT	6000	In line
104	Helium supply pressure gage	------	4000	On regulator 103
105	Helium supply shutoff valve	------	3000	-------------------------------
106	Helium pressure relief valve	------	3000	Set 110 percent of capsule pressure
107	Helium pressure gage	$\frac{1}{4}$ NPT	5000	-------------------------------
108	Helium pressure transducer	------	6000	High and low pressure alarms
109	Relief valve	------	3000	Set at 25 psig (2.75×10^5 N/m^2)
110	Radiation monitor	------	----	At reactor
111	Flow-control valve	------	3000	Micrometer adjustment
112	Flow indicator	1-15-6	200	High and low flow alarms
113	Voltmeter	$4\frac{1}{2}$	----	-------------------------------
114	Ammeter	$4\frac{1}{2}$	----	High-current alarm
115	Frequency meter	$4\frac{1}{2}$	----	0 to 180 cps
116	Gas temperature thermocouple	C. A.	----	Range 0° to 1000° F (0 to 800 K) with high temperature alarm
117	Gas temperature thermocouple	C. A.	----	
118	Gas temperature thermocouple	C. A.	----	
119	Element temperature thermocouple	W-W-Re	----	Range 0° to 3000° F (1460 K) with high temperature alarm
120			----	
121			----	
122			----	
123			----	
124			----	
125			----	



(a) Instrumentation and flow schematic.

Figure 10. - Instrumentation and control components.

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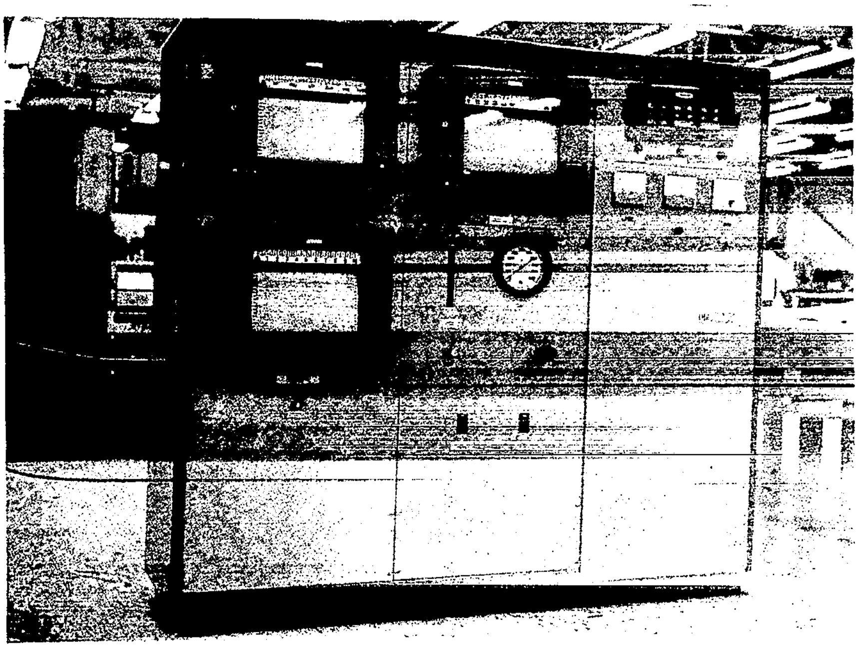

(b) Circulating capsule control console.
Figure 10. - Concluded.

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NASA-Langley, 1969 —— 22 E-4243

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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